Electronic Warfare Division

RESEARCH REPORT
ERL-0523-RR

ANALYSIS OF EMISSION DATA FROM A BROAD-BAND RADIOMETER

by

Soi-Sang Ti, Adrian Tudini and Ray Oermann

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ANALYSIS OF EMISSION DATA FROM A BROAD-BAND RADIOMETER

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SUMMARY

The principles of analysis of emission data from a broad-band radiometer are outlined. The errors arising from the analysis are also discussed and illustrated.

In general, in the determination of radiant output of an emitter using a broad-band radiometer, errors of unknown magnitude will occur unless the spectral emission profile of the calibration source is matched to that of the emitter. Radiometers; Broadband; Emission spectra. (RR)

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1 INTRODUCTION

A broad-band radiometer is an instrument designed and developed to measure the radiant property of an emitter. The spectral passband of the radiometer depends on the detector and the spectral band pass filter selected for the instrument.

In a measurement, the voltage output from the radiometer in response to an incident radiant flux in the waveband of the radiometer is recorded, with time constant normally $\leq$ 100 ms, thus allowing a temporal profile of an emitter to be recorded.

Radiometers are compact, robust and relatively inexpensive instruments extensively used in military applications to collect IR signatures of aircraft, ships, missiles and land vehicles. In IR applications, detectors commonly used are PbSe, PbS, CMT etc.

With a scanning mechanism or using an array of detectors, radiometers have been developed to record the spatial variations of IR emissions of an extended source, eg AGA Thermovision Systems.

In military applications, radiometers are often used to quantify the radiant intensity of an emitter. Because of the broad-band nature of the instrument, analysis of radiometric data needs special consideration. This report outlines the principles of analysis, the sources and magnitude of errors, and the reliable uses of broad-band radiometers to quantify the emission characteristics of an emitter.

2 PRINCIPLES OF ANALYSIS

2.1 Calibration

When a broad-band radiometer is used to determine quantitatively the IR emission of an emitter, it is usually calibrated using a standard blackbody radiating source of a known radiating area and temperature. With a large blackbody at very high temperature (> 1000°C), the calibration can be made directly with the blackbody at the same (large) range as the emitter. However, a blackbody source up to 1000°C often comes with relatively small radiating area, typically $\leq$ 1 cm^2. Consequently, the calibration has to be carried out at a short range and with the collimated blackbody source to produce a reasonable voltage signal.

In the calibration of the broad-band radiometer, the collimated thermal radiation from the blackbody source is incident on the collecting lens of the radiometer. The beam collimation simulates the actual situation in which a broad-band radiometer is used to measure a radiating source at a range » 10 m. The schematic diagram for the calibration is shown in figure 1.

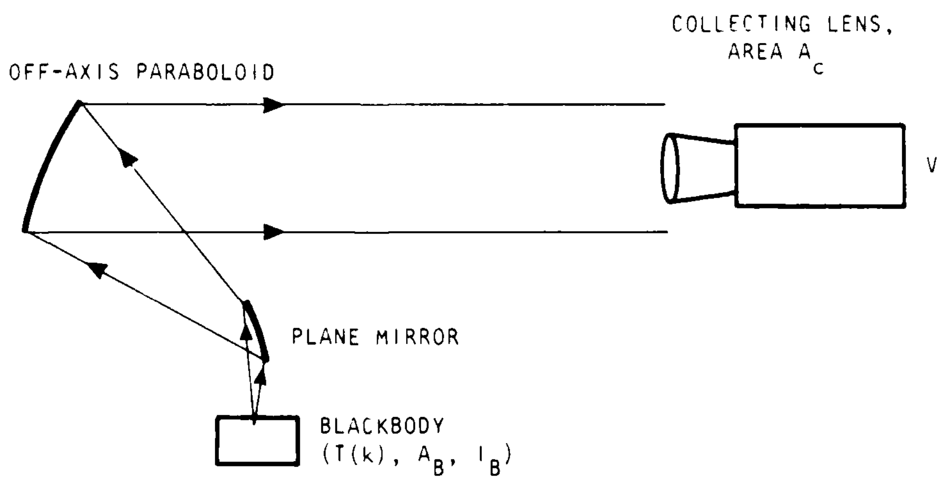

Figure 1 . Schematic diagram for the calibration of a broad band radiometer.

The radiant energy falling on the collecting lens of area Ac, after reflected by the mirrors of reflectivity $r(\lambda)$, is given by Φ:

$$[\Phi]_{\lambda_1}^{\lambda_2} = A_c \frac{1}{f^2} \int_{\lambda_1}^{\lambda_2} r(\lambda)^2 I_B(\lambda)\tau(\lambda,d_B)d\lambda \qquad (1)$$

where $\lambda_1 \rightarrow \lambda_2$ is the spectral passband of the radiometer. f is the focal length of the off-axis paraboloid, and $I_B(\lambda)$ is given by:

$$I_B(\lambda) = \frac{M_B(\lambda)\ A_B}{\pi}\ , \qquad (2)$$

where $M_B(\lambda)$ is the radiant exitance, expressed as

$$M_B(\lambda) = 2\pi hc^2 \frac{1}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda\kappa T}\right) - 1\right]^{-1} \qquad (3)$$

and the atmospheric transmittance $\tau(\lambda,d_B)$ at the range d_B is to be calculated from the Lowtran 6 code. In general, $r(\lambda)$ in the waveband $\lambda_1 \rightarrow \lambda_2$ is approximately constant, and for the ease of representation, $r(\lambda)$ will be written as a constant r.

The single differential voltage output, $[V]_{\lambda_1}^{\lambda_2}$, of the radiometer is

$$[V]_{\lambda_1}^{\lambda_2} = k\int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\phi(\lambda)d\lambda \qquad (4)$$

where $\phi(\lambda)$ is the spectral response function of the broad-band radiometer, and k is a proportionality constant. Substituting equation (1) in equation (4):

$$[V]_{\lambda_1}^{\lambda_2} = k\ A_c r^2 \frac{1}{f^2} \int_{\lambda_1}^{\lambda_2} I_B(\lambda)\tau(\lambda,d_B)\phi(\lambda)d\lambda \qquad (5)$$

By plotting

$$[V]_{\lambda_1}^{\lambda_2} \text{ versus } A_c \frac{r^2}{f^2} \int_{\lambda_1}^{\lambda_2} I_B(\lambda)\tau(\lambda,d_B)\phi(\lambda)\,d\lambda$$

where the former is a measured quantity and the latter a calculated quantity, a linear calibration plot is obtained, and the gradient is numerically equal to k. Note that an identical integrated value may result from different $I_B(\lambda,T)$ s . i.e .

$$\left.\begin{aligned} &\int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_1)\tau(\lambda,d_B)\phi(\lambda)d\lambda \\ &= \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_2)\tau(\lambda,d_B)\phi(\lambda)d\lambda \\ &\quad\vdots \\ &\quad\vdots \\ &= \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_n)\tau(\lambda,d_B)\phi(\lambda)d\lambda \end{aligned}\right\} \tag{6}$$

even though

$$\left.\begin{aligned} &\int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_1)\tau(\lambda,d_B)d\lambda \\ &\neq \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_2)\tau(\lambda,d_B)d\lambda \\ &\quad\vdots \\ &\quad\vdots \\ &\neq \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T_n)\tau(\lambda,d_B)d\lambda \end{aligned}\right\} \tag{7}$$

Expression (7) suggests that the incident radiant fluxes of different magnitude in the waveband λ_1 to λ_2 will generate an identical voltage output in the radiometer. Further, the calibration constant k in equation (5) is independent of $\int_{\lambda_1}^{\lambda_2} I_B(\lambda,T)\tau(\lambda,d_B)d\lambda$.

The advantage of including the spectral response function of the radiometer in the analysis (equation (5)) is that the limits of the radiometer wavebands are automatically imposed. It also allows the blackbody at different temperatures to be used in the calibration while keeping the range constant. However, when the actual radiant output of an emitter is to be determined using the the calibration constant k, the real spectral profile of the radiator must be specified.

Alternatively , a calibration in which $[V]_{\lambda_1}^{\lambda_2}$ versus $[\Phi]_{\lambda_1}^{\lambda_2}$ can be plotted , $[\Phi]_{\lambda_1}^{\lambda_2}$ is expressed as $\frac{A_c}{f^2} r^2 \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T)\tau(\lambda,d_B)d\lambda$, given in equation (1). In this calibration, a single blackbody temperature as close as possible to the temperature of the unknown grey /black body must be used, while the emitting area and the range adjusted to yield a wide range of $[V]_{\lambda_1}^{\lambda_2}$. i.e.

$$[V]_{\lambda_1}^{\lambda_2} = k(T)\frac{A_c}{f^2} r^2 \int_{\lambda_1}^{\lambda_2} I_B(\lambda,T)\tau(\lambda,d_B)d\lambda \tag{8}$$

Every linear plot will have a gradient k(T) characteristic of the spectral profile $I_B(\lambda,T)$.

2.2 Radiant intensity determination

When the calibrated radiometer is used to measure the radiant output of a radiating source the differential voltage output is written either as:

$$[V]_{\lambda_1}^{\lambda_2} = kA_c \frac{1}{d_s^2} \int_{\lambda_1}^{\lambda_2} I_s(\lambda)\tau(\lambda, d_s)\phi(\lambda)d\lambda \qquad (9)$$

or

$$[V]_{\lambda_1}^{\lambda_2} = k(T)A_c \frac{1}{d_s^2} \int_{\lambda_1}^{\lambda_2} I_s(\lambda)\tau(\lambda, d_s)d\lambda \qquad (10)$$

where $[V]_{\lambda_1}^{\lambda_2}$ is a numerically measured quantity, and k or k(T) the calibration constant previously determined. The radiant intensity of the unknown emitter is then evaluated under two following cases:

(a) <u>Case 1</u>: <u>An emitting source with a known $I_S(\lambda)$ profile</u>.

When the spectral profile of an emitting source is known, the normalised form, $i_S(\lambda)$, in the waveband λ_1 to λ_2 can be constructed. Equations (9) and (10) can be written as:

$$[V]_{\lambda_1}^{\lambda_2} = kA_c \frac{1}{d_s^2} I \int_{\lambda_1}^{\lambda_2} i_s(\lambda)\tau(\lambda, d_s)\phi(\lambda)d\lambda \qquad (11)$$

or

$$[V]_{\lambda_1}^{\lambda_2} = k(T)A_c \frac{1}{d_s^2} I \int_{\lambda_1}^{\lambda_2} i_s(\lambda)\tau(\lambda, d_s)d\lambda \qquad (12)$$

where I is the only unknown scalar to be determined from equations (11) and (12). The knowledge of I allows the radiant intensity of the emitter in the waveband λ_1 to λ_2 to be found from:

$$[I]_{\lambda_1}^{\lambda_2} = I \int_{\lambda_1}^{\lambda_2} i_s(\lambda)d\lambda \qquad (13)$$

(b) <u>Case 2</u>: <u>An emitting source with an unknown $I_S(\lambda)$ profile</u>

In the event that the spectral emission profile of an emitter is <u>not</u> known, a concept of equivalent blackbody is used. This involves an assumption that the spectral profile of the emitter resembles that of the blackbody used for calibration. The radiant intensity analysed for the emitter is then the equivalent blackbody [T(K)] radiant intensity of the emitter.

In this case , errors of unknown magnitude will occur and the extent depends on the degree of discord between the spectral profiles of the calibration source and the emitter.

3 ILLUSTRATIONS

In the foregoing section it is mentioned that the radiant output of an emitter analysed from emission data measured by a broad-band radiometer entails errors, if the actual spectral profile of the emitter is not known, and the magnitude of which depends on the extent of mismatch between the spectral profiles of the calibration source and the emitter. Illustrations will be given to exemplify the sources of errors.

3.1 Radiant intensity of an unknown blackbody emitter

A broad-band radiometer equipped with PbSe detector was used to measure the emission of an unknown blackbody radiator. The PbSe radiometer has the spectral response function as shown in figure 2, with the spectral passband being 2.3µm to 6.0µm. A dip at 4.3µm is attributable to the atmospheric attenuation by $C0_2$ inside the radiometer.

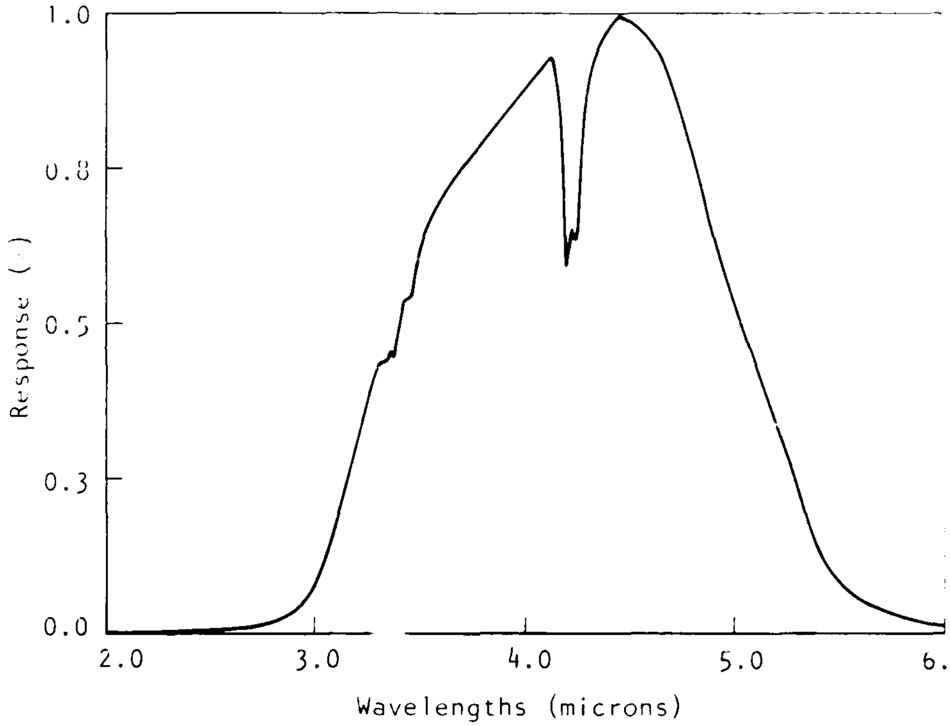

Figure 2 . Spectral response function of a PbSe radiometer.

3.1.1 Calibration of a PbSe radiometer

In calibrating the PbSe radiometer, a standard blackbody at temperatures 806°C, 846°C and 1064°C was used. A calibration plot was obtained by varying the radiating area of the calibration blackbody source. A plot of

$$[V]_{2.3\mu m}^{6.0\mu m} \quad \text{versus} \quad A_c \frac{r^2}{f^2} \int_{2.3\mu m}^{6.0\mu m} I_B(\lambda, 846^\circ C)\varphi(\lambda)\tau(\lambda, d_B)d\lambda$$

yielded a straight line with gradient k equal to 5.50 x 10^5 V/W (figure 3). k is constant irrespective of the temperature of the blackbody source (see equation (5)). This plot has masked the fact that different radiant fluxes $[\Phi]_{\lambda_1}^{\lambda_2}$ at the front end of the instrument will produce a single voltage output in the PbSe radiometer.

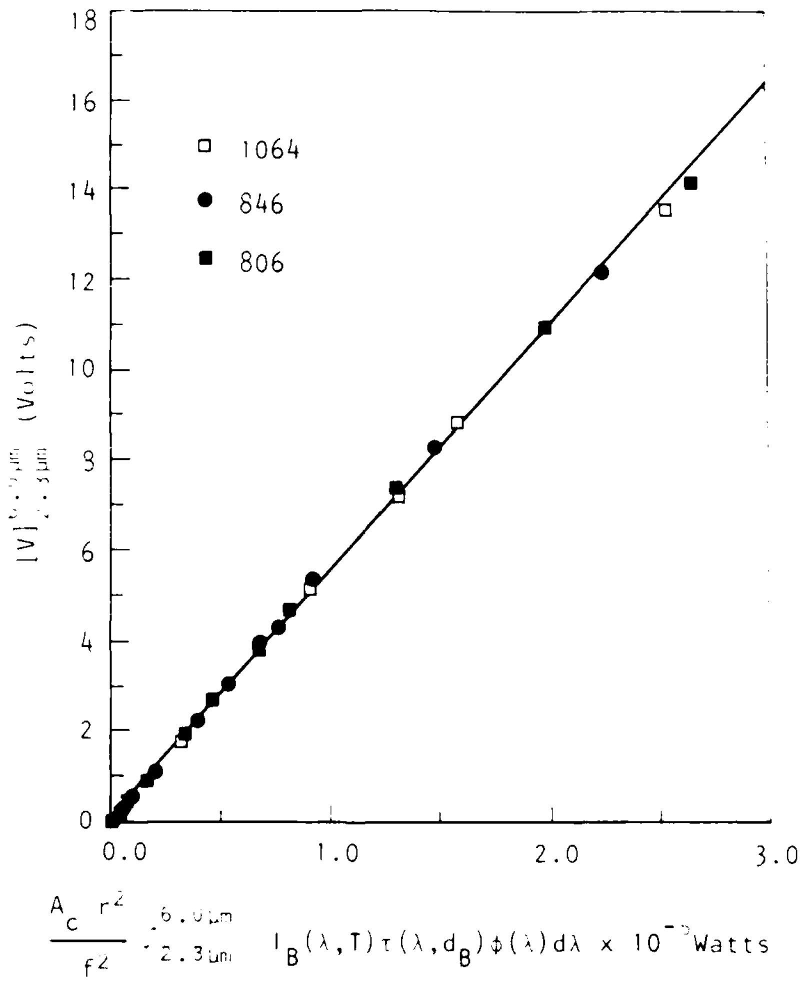

Figure 3. Calibration plot of a PbSe radiometer

When $[V]_{2.3\mu m}^{6.0\mu m}$ was plotted against $[\Phi]_{2.3\mu m}^{6.0\mu m}$ where $[\Phi]_{2.3\mu m}^{6.0\mu m}$ is the radiant flux falling on the front end optics of the radiometer, given by equation (1), calibration plots of different gradients were obtained, as shown in figure 4. i.e.,

$$[V]_{2.3\mu m}^{6.0\mu m} = k(T)\frac{A_c r^2}{f^2}\int_{2.3\mu m}^{6.0\mu m} I_B(\lambda,T)\tau(\lambda,d_B)d\lambda \qquad (14)$$

where k (T) is temperature dependent. It implies that the value of k(T) depends on the spectral emission profile of the emitter.

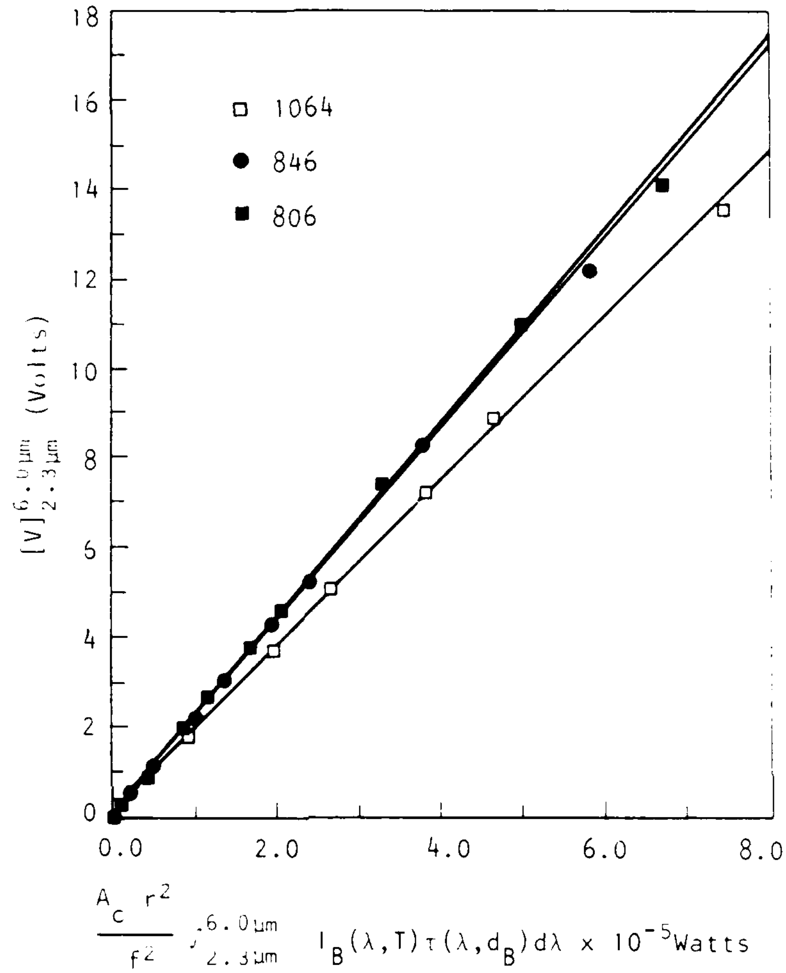

Figure 4. Plot of voltage output of a PbSe radiometer versus incident radiant fluxes.

The inability of the broad-band radiometer to resolve the incident radiant fluxes is clearly demonstrated in figure 4 , in which a single voltage output of the radiometer was generated by incident radiant energy of different magnitude dictated by the spectral profiles of $I_B(\lambda,T)$.

3.1.2 Determination of radiant intensity

In illustrating the effect of spectral profiles between the emitter and the calibration source , the blackbody at 846°C was arbitrarily cho~en as the calibration source. The relationship between the actual radiant flux falling on the radiometer to produce a corresponding voltage is given by the linear plot marked T(846°C) in figure 4.

The "unknown" radiators are simulated by the blackbody at temperatures 806°C, 846°C and 1064°C . It is to be noted that high temperature blackbody radiators were used so that the ambient contribution appeared to be negligibly small. The radiating area and the range were adjusted so that a constant output voltage was recorded. The numerical voltage output of the radiometer measured was <u>10.0 volts</u> and, following equation (11), is written as:

$$[V]_{2.3\mu m}^{6.0\mu m} = k\frac{A_c}{d_S^2} I\int_{2.3\mu m}^{6.0\mu m} i_S(\lambda,T)\phi(\lambda)\tau(\lambda,d_S)\,d\lambda \qquad (15)$$

All quantities were known except the scalar I, which was readily determined. The radiant intensity of the emitter was then computed from equation (13):

$$|I|_{2.3\mu m}^{6.0\mu m} = I \int_{2.3\mu m}^{6.0\mu m} i_S(\lambda, T)\, d\lambda \tag{16}$$

At the identical voltage output of the PbSe radiometer, the radiant intensity of the calibration blackbody source at 846°C was calculated from equation (12) and (13).

Table 1 presents the radiant intensity analysed for each "unknown" radiator, and also the error compared with the radiant intensity of the calibration blackbody (846°C) source at the identical voltage output of the PbSe radiometer.

Table 1 Radiant intensities and errors analysed for the "unknown" blackbody radiators from a PbSe radiometer with an identical voltage output.

Calibration Source (B)		Emitting Source (S)		Error
T_B(°C)	I_B(Wsr^{-1})	T_S(°C)	I_S(Wsr^{-1})	I_B/I_S
846	0.158	806	0.154	1.03
		846	0.158	1.00
		1064	0.179	0.88

From Table 1, it is observed that the radiant intensity of 0.158 W Sr^{-1} from the calibration source (at 846°C) will generate a voltage output of 10.0 volts on the PbSe radiometer. Hence, when the radiometer is used to measure an unknown emitter which produces a voltage of 10.0 volts, a radiant intensity of 0.158 W Sr^{-1} will be implicated.

This value is <u>lower</u> than the radiant output of the emitter at 1064°C but <u>higher</u> than that at 806°C, which are respectively 0.179 W Sr^{-1} and 0.154 W Sr^{-1} (note that both these radiant outputs generated 10.0 volts on the PbSe radiometer). Hence the following remarks are note worthy:

(a) For quantification of radiant output of an emitter using a broad-band radiometer, the radiant intensity of the emitter can be accurately determined if the spectral emission profile of the emitter is known and is in agreement with that of the calibration source.

(b) The magnitude of error increases as the extent of spectral accord decreases.

(c) For the emitter having emission spectral profile different from that of the calibration source, the magnitude of error increases with the measured voltage output of the radiometer, as illustrated in figure 4.

(d) In so far as the analysis of radiant data from the blackbody type of emitting source using the PbSe radiometer is concerned, the radiant intensity is underestimated if its temperature is higher than that of the calibration source . The converse is also true .

A field evaluation of the broad-band radiometers will be illustrated in the next section.

3.2 Radiant intensity of IR flares

IR flares consisting of M_g and PTFE propellants radiate like a grey/blackbody at temperature ≈ 2000 K [Ti et al 1989A]. The radiant output varies correspondently to the burn rate of the propellants.

In the measurement of IR emission characteristics of the flares, two PbSe radiometers (passband 2.3 to 6.0μm) and two InSb radiometers (passband 3.9 to 5.3μm) were used in conjunction with a Perkin-Elmer 1710 FTIR spectrometer preset with a spectral resolution of $16cm^{-1}$. From the time-dependent radiant intensities analysed from the emission data recorded by the broad-band radiometers, the average radiant intensity over the burn time of the flare was calculated. The average radiant intensities in the relevant spectral passbands were then compared to the time-average radiant intensity calculated from the FTIR. The FTIR has a high spectral resolution and will provide a reliable means for accurate analysis of emission data [Tudini and Ti 1989B].

Table 2 Radiant intensity of IR flares analysed from PbSe and InSb radiometers and a Perkin-Elmer 1710 FTIR *.

Flare	Spectral passband	Av. Radiant intensity (kW_{sr}^{-1})				
		PbSe (1)	PbSe (2)	FTIR	InSb (1)	InSb (2)
5	2.3 - 6.0	9.8	9.0	9.4	---	---
5	3.9 - 5.3	---	---	2.0	---	---
8	3.9 - 5.3	---	---	---	2.1	2.1

* Spectral profile of the flare is similar to that of a blackbody at 2000 k.

From Table 2, it is observed that the radiant intensities analysed from the broad-band radiometers in their respective spectral passbands are in good agreement with those analysed from the FTIR, with errors within ± 5 %. The agreement is attributed to the fact that the true spectral profile of the flares was used in the analysis, or the spectral profile of the flares matched that of the calibration source in the spectral wavebands of interest.

Evidently, radiant output of an emitter can be evaluated confidently by a broad-band radiometer if spectral accord exists between the emitter and the calibration source.

3.3 Equivalent blackbody radiant intensity at T(K)

The previous section exemplifies the use of broad-band radiometers in quantifying the IR signature of an emitter. In the event that a reasonable agreement exists between the spectral profiles of the calibration and the emitter sources, the broad-band radiometer does provide good and reliable radiant intensity data. Moreover, providing that the spectral emission profile of an emitter does not vary in the course of measurement, the broad-band radiometer yields an invaluable record on the time-dependent nature of the radiant output, i.e. the temporal profile.

In the circumstances in which only broad-band radiometers are available to quantify the radiant output of an emitter, the spectral profile of which is not available, a concept of "equivalent blackbody radiant intensity at T(K)" may be used. Basically, the radiant intensity of the emitter is described as equivalent to X times that of the calibration blackbody at T(K), expressed in W sr^{-1}, perceived by a particular radiometer. It has limited applications since:

(i)It does not represent the true radiant output of the emitting source, unless an accord of the spectral profiles exists between the emitter and the calibration source; and

(ii)it does not provide a realistic comparison of radiant output of two emitters unless they have similar spectral emission profiles, and the radiometer is calibrated with the blackbody of identical temperatures.

4 CONCLUSION

Following the analysis, it is evident that a broad-band radiometer cannot be used straightforwardly to measure the radiant output of an emitter, unless the spectral emission profile of the calibration source is matched to that of the emitter. In general, the magnitude of error increases with the degree of spectral discord.

5 ACKNOWLEDGEMENTS

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17 SUMMARY OR ABSTRACT
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